## Ultraluminous Infrared Galaxies at $1.5 < z < 3$ occupy dark matter haloes of mass $\sim 6 \times 10^{13} M_\odot$

D. Farrah[1], C. J. Lonsdale[2,6], C. Borys[3], F. Fang[2], I. Waddington[4], S. Oliver[4], M. Rowan-Robinson[5], T. Babbedge[5], D. Shupe[2], M. Polletta[6], H. E. Smith[6], J. Surace[2]

**Abstract.**    We present measurements of the spatial clustering of ultraluminous infrared galaxies in two redshift intervals, $1.5 < z < 2.0$ and $2 < z < 3$. Both samples cluster strongly, with $r_0 = 14.40 \pm 1.99 h^{-1}$Mpc for the $2 < z < 3$ sample, and $r_0 = 9.40 \pm 2.24 h^{-1}$Mpc for the $1.5 < z < 2.0$ sample, making them among the most biased galaxies at these epochs. These clustering amplitudes are consistent with both populations residing in dark matter haloes with masses of $\sim 6 \times 10^{13} M_\odot$. We infer that a minimum dark matter halo mass is an important factor for all forms of luminous, obscured activity in galaxies at $z > 1$. Adopting plausible models for the growth of DM haloes with redshift, then the haloes hosting the $2 < z < 3$ sample will likely host the richest clusters of galaxies at z=0, whereas the haloes hosting the $1.5 < z < 2.0$ sample will likely host poor to rich clusters at z=0.

### 1. Introduction

When we look at the night sky, we see that galaxies seem to be arranged in a particular way. One might expect that galaxies would be distributed randomly, much as grains of sand would if you threw a handful across the floor, but instead, they seem to trace elegant structures; galaxy clusters are connected to each other by long filaments, interspersed with large voids, where few or no galaxies are seen. The drivers behind the formation of these 'large-scale structures' have been the subject of intense study and debate for over thirty years; how did the Universe go from being smooth and homogeneous just after the Big Bang to the clumpy, clustered Universe we see today?

At the core of current theories for the formation of these structures is the premise that the evolution of the total mass distribution is described by the gravitational collapse of primordial density fluctuations, and that this evolution is traced by the evolution of galaxies. Overdense regions, or 'haloes', are

[1]Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

[2]IPAC, California Institute of Technology, Pasadena, CA 91125, USA

[3]Department of Astronomy, University of Toronto, Toronto, Canada

[4]Astronomy Center, University of Sussex, Falmer, Brighton, UK

[5]Astrophysics Group, Imperial College, London SW7 2BW, UK

[6]CASS, University of California at San Diego, La Jolla, CA 92093, USA

predicted to undergo mergers to build haloes of increasing mass, with galaxies forming from the baryonic matter in these haloes. This framework of 'biased' hierarchical buildup (Cole et al 2000; Hatton et al 2003) has proven to be remarkably successful in explaining several important aspects of galaxy and large-scale structure formation.

This paradigm is however not without its problems. A good example of these problems concerns the evolution of massive ($\geq 10^{11} M_{\odot}$) galaxies. We might expect that massive galaxies form slowly, with many halo mergers needed to build up the required large baryon reservoirs, and indeed some galaxies do appear to form in this way (van Dokkum et al 1999; Bell et al 2004). There is however evidence that many massive galaxies may form at high redshift (Dunlop et al 1996; Blakeslee et al 2003) and on short timescales (Ellis et al 1997), directly counter to early, 'naive' model predictions. Intriguingly, recent surveys (e.g. Eales et al 2000; Scott et al 2002) have uncovered a huge population of distant, IR bright sources that are plausible candidates for being rapidly forming, massive galaxies, however they are so numerous that even recent models have difficulty in explaining their counts, and invoke a wide variety of solutions (e.g. Baugh et al (2005)).

It seems likely therefore that there are strong, but subtle links between distant, IR/sub-mm bright galaxies, and the formation of large-scale structures. Therefore, we need observations that relate the properties of these galaxies with the underlying dark matter distribution. Motivated by this, we have used data from the Spitzer Wide Area Infrared Extragalactic Survey (SWIRE, Lonsdale et al (2003)) to select large samples of distant Ultraluminous Infrared Galaxies (ULIRGs, $L_{ir} \geq 10^{12} L_{\odot}$) and study their clustering evolution with redshift. We assume $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, $\Omega = 1$, and $\Omega_{\Lambda} = 0.7$. The results presented here were originally published in Farrah et al. (2006a,b).

## 2.   Analysis and results

To select high redshift ULIRGs, we use the 1.6$\mu$m emission feature, which arises due to photospheric emission from evolved stars. When this feature is redshifted into one of the IRAC channels then that channel exhibits a 'bump' (Simpson & Eisenhardt 1999; Sawicki 2002). A complete discussion of the source selection and characterization methods is given in Lonsdale et al 2006 (in preparation), which we summarize here.

Our sources are taken from the ELAIS N1 and ELAIS N2 fields, and the Lockman Hole, covering 20.9 square degrees in total. We first selected those sources fainter than R=22 (Vega), and brighter than 400$\mu$Jy at 24$\mu$m. Within this set, we selected two samples that displayed a 'bump' in the 4.5$\mu$m and 5.8$\mu$m channels, i.e. where $f_{3.6} < f_{4.5} > f_{5.8} > f_{8.0}$ for one sample (the 'B2' sample) and where $f_{3.6} < f_{4.5} < f_{5.8} > f_{8.0}$ for the other sample (the 'B3' sample). This resulted in a total of 1689 B2 sources and 1223 B3 sources.

For both samples we used HYPER-Z (Bolzonella et al 2000) to estimate redshifts, the results from which place most of the B2 sources within $1.5 < z < 2.0$, and most of the B3 sources within $2.2 < z < 2.8$. From the best fits we also derived IR luminosities and power sources; the requirement that the sources have $f_{24} > 400\mu$Jy demands an IR luminosity of $\geq 10^{12} L_{\odot}$ for all the sources,

with (most objects having) a starburst as the dominant power source, with star formation rates of $\geq 200 M_\odot yr^{-1}$. Similarly, the presence of the $1.6\mu m$ feature demands a minimum mass of evolved stars of $\sim 10^{11} M_\odot$. Both the B2 and B3 sources are thus good candidates for being moderately massive galaxies harboring an intense, obscured starburst, making them similar in nature to both local ULIRGs, and high-redshift SMGs.

We measured the angular clustering of both samples using the methods described in Farrah et al. (2006a,b), which we summarize here. We found that the levels of angular clustering seen in the three fields were consistent with each other to within $0.5\sigma$, and so combined the angular clustering measures for each sample over the three fields. To quantify the strength of clustering, we fit both datasets with a power law, $\omega(\theta) = A_\omega \theta^{1-\gamma}$, where $\gamma = 1.8$ and $A_\omega$ is the clustering amplitude; $A_\omega = 0.0125 \pm 0.0017$ for the B3s and $A_\omega = 0.0046 \pm 0.0011$ for the B2s. To convert these angular clustering amplitudes to spatial clustering amplitudes, we invert Limbers equation:

$$\frac{r_0(z)}{f(z)} = \left[ \frac{H_0^{-1} A_\omega cC \left[ \int_a^b \frac{dN}{dz} dz \right]^2}{\int_a^b \left( \frac{dN}{dz} \right)^2 E(z) D_\theta^{1-\gamma}(z) f(z)(1+z)dz} \right]^{\frac{1}{\gamma}} \qquad (1)$$

where $f(z)$ parametrizes the redshift evolution of $r_0$, and:

$$C = \frac{\Gamma(\gamma/2)}{\Gamma(1/2)\Gamma([\gamma-1]/2)}, E(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{\frac{1}{2}} \qquad (2)$$

We derived $dN/dz$ from the photometric redshift distributions (Lonsdale et al 2006). For the B2 sources this is a Gaussian centered at $z = 1.7$ with a FWHM of 1.0, and for the B3 sources this is a Gaussian centered at $z = 2.5$ with a FWHM of 1.2. The resulting correlation lengths are $r_0 = 9.4 \pm 2.24 h^{-1} Mpc$ for the B2 sources, and $r_0 = 14.4 \pm 1.99 h^{-1} Mpc$ for the B3 sources.

## 3.   Discussion

To place these clustering results in context, we consider two models. The first parametrizes the spatial correlation function, $\xi$, as a single power law in comoving coordinates, where the comoving correlation length, $r_0(z)$, is:

$$r_0(z) = r_0 f(z), f(z) = (1+z)^{\gamma-(3+\epsilon)} \qquad (3)$$

Here the choice of $\epsilon$ determines the redshift evolution (Phillipps et al. 1978; Overzier et al 2003). Several cases are usually quoted. First is 'comoving clustering', where haloes expand with the Universe, and $\epsilon = \gamma - 3$; in this case clustering remains constant. Second is the family of models for which $\epsilon \geq 0$, for which clustering increases with time. Examples of this family include (a) 'stable' clustering, for which $\epsilon \simeq 0$ (in this case the haloes are frozen in *proper* coordinates, (b) the predicted evolution of clustering of the overall dark matter distribution, where $\epsilon \simeq \gamma - 1$ (Carlberg et al 2000), and $r_0 \simeq 5$ at z=0 (Jenkins et al 1998), (c) 'linear' clustering, where $\epsilon = 1.0$. A cautionary note to this is that detailed interpretations of clustering evolution from these models

suffer from several theoretical flaws (Moscardini et al 1998; Smith et al. 2003), and so should be thought of as qualitative indicators rather than quantitative predictions. We therefore simply use the 'stable' and 'linear' models as indicators of the possible range of halo clustering amplitude with redshift.

The second class of model comprises those in which comoving correlation lengths increase with *increasing* redshift. These models introduce 'bias', $b(z)$, between the galaxies and the underlying dark matter. An example of such models are the 'fixed mass' models (Matarrese et al 1997; Moscardini et al 1998), which predict the clustering strength of haloes of a specified mass at any given redshift. In Figure 1 we plot the $\epsilon$ model for dark matter, 'stable'and 'linear' epsilon models normalized to the B2 and B3 clustering strengths, the fixed halo mass models for halo masses of $10^{12}M_{\odot}$, $10^{13}M_{\odot}$, and $10^{14}M_{\odot}$, the $r_0$ values for the B2 and B3 galaxies, and the spatial correlation lengths of other galaxy populations taken from the literature.

With the the uncertainties described earlier firmly in mind, we use Figure 1 to explore the relationships between our samples, the underlying dark matter, and other galaxies. Both the B2s and the B3s are strongly clustered, with correlation lengths much higher than that predicted for the overall DM distribution. Both B2s and B3s cluster significantly more strongly than optical QSOs at their respective epochs, and B3s cluster more strongly than SMGs. Based on the Matarrese et al (1997) models, then we derive *approximate* $1\sigma$ halo mass ranges of $10^{13.7} <M_{\odot} < 10^{14.1}$ for the B3s, and $10^{13.5} <M_{\odot} < 10^{13.9}$ for the B2s. Interestingly, halo masses comparable to these were recently derived for an independent sample of high-redshift ULIRGs by Magliocchetti et al. (2007).

The most interesting comparison is however between the two samples themselves. The clustering evolution of QSOs with redshift (Croom et al. 2005) may mean that there is a 'minimum' host halo mass for QSO activity, below which no QSO is seen, of $\sim 5 \times 10^{12}M_{\odot}$. The correlation lengths for the B2 and B3 samples are consistent with the same conclusion but for a $\sim 6 \times 10^{13}M_{\odot}$ 'minimum' DM halo mass. Taken together, these results imply that a minimum halo mass is a 'threshold' factor for *all* forms of luminous activity in galaxies, both starbursts and AGN. It is also interesting to speculate on what the host haloes of B2 and B3 sources contain at lower and higher redshifts. We might expect that a halo hosting a B3 source could contain an optically bright LBG at $z \sim 4$, followed by a B3 at $z \sim 2.5$, possibly accompanied by other (near-IR selected) star forming systems (Daddi et al. 2004, 2005), before evolving to host a rich galaxy cluster at low redshifts. The occupants of a halo hosting a B2 galaxy would however probably be different. We would expect that such a halo could contain an SMG at $z \sim 2.5$, and optically fainter LBGs at $4 < z < 5$ (though probably not LBGs at $z \sim 3$). At lower redshifts such a halo might host a radio-bright AGN and or ERO at $z \sim 1$, and a (poor to rich) cluster at $z = 0$. We conclude that ULIRGs at $z \geq 1.5$ as a class likely signpost stellar buildup in galaxies in clusters at $z = 0$, with higher redshift ULIRGs signposting stellar buildup in galaxies that will reside in more massive clusters at lower redshifts.
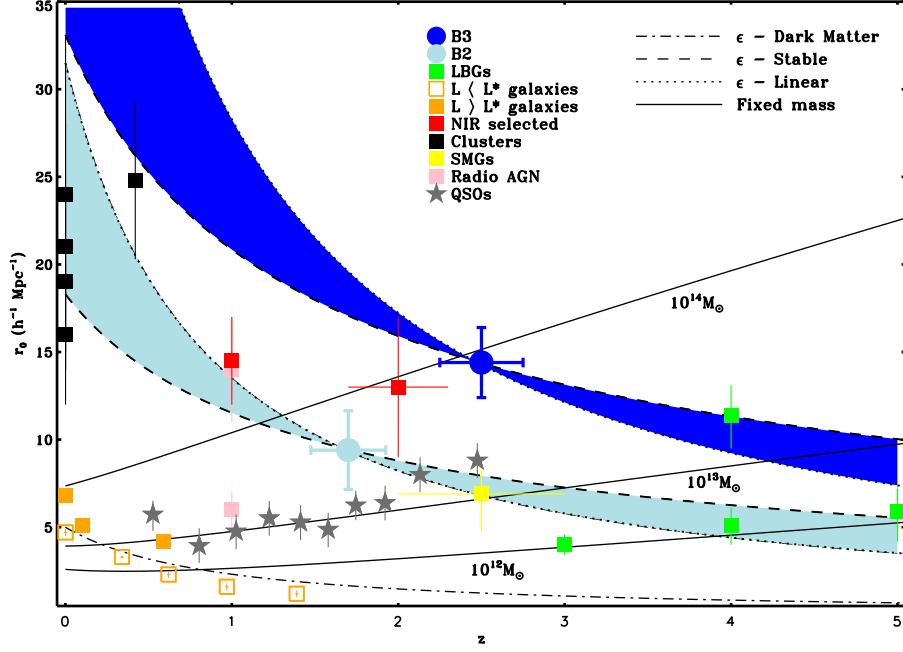
**Figure 1.** Comoving correlation length, $r_0$, vs. redshift. Other data are taken from Moscardini et al 1998; Overzier et al 2003; Daddi et al. 2004; Blain et al 2004; Ouchi et al. 2004; Adelberger et al. 2005; Croom et al. 2005; Georgakakis et al. 2005; Allen et al. 2005. The 'Fixed mass' lines show the predicted clustering amplitude of haloes of a given mass at any particular redshift, whereas the $\epsilon$ lines show the predicted clustering amplitude of an individual halo for three halo growth models, described in the text. The 'Stable' and 'Linear' lines give a qualitative indicator of the range of how DM haloes may grow with redshift, and we have normalized 'Stable' and 'Linear' lines to the clustering amplitudes of the B2s and the B3's. The shaded regions therefore indicate what these haloes may host at lower and higher redshifts - the haloes hosting B3s may contain an optically bright LBG at $z \simeq 4$ (upper green point), and grow to host very rich galaxy clusters at z=0, whereas the haloes hosting B2 sources may contain optically fainter LBGs at $4 < z < 5$, SMGs at $z \sim 2.5$, radio-bright AGN (upper pink triangle) and (old) EROs at $z \simeq 1$, and poor to rich clusters at z=0.

# References

Adelberger, K. L., Steidel, C. C., Pettini, M., Shapley, A. E., Reddy, N. A., & Erb, D. K. 2005, ApJ, 619, 697

Allen, P. D., Moustakas, L. A., Dalton, G., MacDonald, E., Blake, C., Clewley, L., Heymans, C., & Wegner, G. 2005, MNRAS, 360, 1244

Baugh, C. M., Lacey, C. G., Frenk, C. S., Granato, G. L., Silva, L., Bressan, A., Benson, A. J., & Cole, S. 2005, MNRAS, 356, 1191

Bell, E. F., et al 2004, ApJ, 608, 752

Blain A. W., Chapman S. C., Smail I., Ivison R., 2004, ApJ, 611, 725

Blakeslee, J. P., et al 2003, ApJ, 596, L143

Bolzonella M., Miralles J.-M., Pello R., 2000, A&A, 363, 476

Carlberg, R. G., Yee, H. K. C., Morris, S. L., Lin, H., Hall, P. B., Patton, D., Sawicki, M., & Shepherd, C. W. 2000b, ApJ, 542, 57

Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168

Croom S. M., et al. 2005, MNRAS, 356, 415

Daddi, E., et al. 2004, ApJ, 600, L127

Daddi, E., et al. 2005, ApJ, 631, L13

Dunlop J., Peacock J., Spinrad H., Dey A., Jimenez R., Stern D., Windhorst R., 1996, Nat, 381, 581

Eales S., Lilly S., Webb T., Dunne L., Gear W., Clements D., Yun M., 2000, AJ, 120, 2244

Ellis R. S., Smail I., Dressler A., Couch W. J., Oemler A., Butcher H., Sharples R. M., 1997, ApJ, 483, 582

Farrah, D., et al. 2006, ApJ, 641, L17

Farrah, D., et al. 2006, ApJ, 643, L139

Georgakakis, A., Afonso, J., Hopkins, A. M., Sullivan, M., Mobasher, B., & Cram, L. E. 2005, ApJ, 620, 584

Governato, F., Baugh, C. M., Frenk, C. S., Cole, S., Lacey, C. G., Quinn, T., & Stadel, J. 1998, Nat, 392, 359

Hatton, S., Devriendt, J. E. G., Ninin, S., Bouchet, F. R., Guiderdoni, B., & Vibert, D. 2003, MNRAS, 343, 75

Jenkins A., et al, 1998, ApJ, 499, 20

Lonsdale C. J., et al, 2003, PASP, 115, 897

Lonsdale, C., et al 2006, ApJ, in preparation

Magliocchetti, M., et al, 2007, MNRAS submitted, astroph 0611409

Matarrese, S., Coles, P., Lucchin, F., & Moscardini, L. 1997, MNRAS, 286, 115

Moscardini, L., Coles, P., Lucchin, F., & Matarrese, S. 1998, MNRAS, 299, 95

Ouchi, M., et al. 2004, ApJ, 611, 685

Overzier R. A., Rottgering H. J. A., Rengelink R. B., Wilman R. J., 2003, A&A, 405, 53O

Phillipps, S., Fong, R., Fall, R. S., & MacGillivray, H. T. 1978, MNRAS, 182, 673

Sawicki, M. 2002, AJ, 124, 3050

Scott S. E., et al, 2002, MNRAS, 331, 817

Simpson, C., & Eisenhardt, P. 1999, PASP, 111, 691

Smith, R. E., et al. 2003, MNRAS, 341, 1311

van Dokkum, P. G., Franx, M., Fabricant, D., Kelson, D. D., & Illingworth, G. D. 1999, ApJ, 520, L95